Application Note

TAS6x84-Q1 LC Filter Selection Guide

Derek Gong, Ronan Liu

ABSTRACT

TI's digital input automotive Class-D audio amplifier, TAS6x84-Q1, supports 384kHz, 480kHz, and up to 2MHz switching frequencies. An LC filter on the output of the amplifier is required to remove the fundamental switching frequency noise. Proper component selection of the LC filter is critical to meet the desired audio performance, efficiency, EMC requirements, and cost for the end application. This application report serves as a guide to aid in the selection of an LC filter for TAS6x84-Q1 to meet target-design goals of the end system.

Table of Contents

List of Figures

List of Tables

1 Introduction

There are several existing application notes on determining the proper LC filter for class-D amplifiers, such as *LC Filter Design* and *Inductor Selection Guide for 2.1MHz Class-D Amplifiers*, that discuss considerations when determining the output LC filter configuration, inductor values, and capacitor values.

TAS6x84-Q1 is a high-power class-D audio amplifier, supporting up to 45V voltage and at least 10A current per channel, and uses BD or 1SPW mode modulation. Figure 1-1 shows the LC filter single-ended equivalent circuit. BD and 1SPW mode modulation use same LC filter configuration.

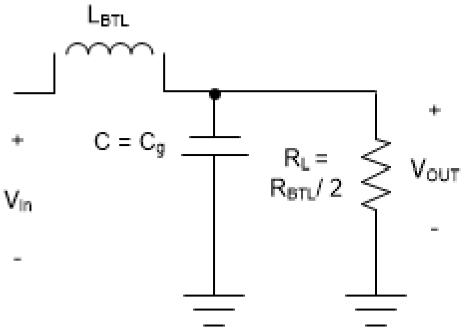


Figure 1-1. LC Filter for BD and 1SPW Mode (Half is Shown)

Ripple current on the inductors is defined as the alternating current flowing through the output inductor of a class-D amplifier. With an LC filter, specifically as the cutoff frequency of the LC filter is reduced relative to the PWM switching frequency of the amplifier, the ripple current is reduced such that only a small residual ripple voltage is present after the LC filter. Lower ripple current is also desired in LC filter design to reduce power loss across the $R_{DS(on)}$ of the output FETs and the DCR of the output inductors, and EMC radiation interference.

The ripple current contributes the most to the total idle current. Figure 1-2 shows that when in BD modulation mode, class-D amplifiers produce a common-mode voltage of PVDD / 2 after the LC filter at idle, which is the average value of the 50% duty-cycle PWM switching waveform (see Figure 1-3).

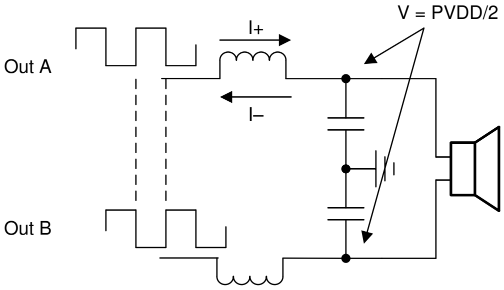


Figure 1-2. PVDD / 2 Common-Mode Voltage

Therefore, the voltage across the output inductor changes the polarity when the PWM voltage reaches PVDD / 2. The maximum voltage across the inductor is PVDD / 2 and the minimum voltage is –PVDD / 2.

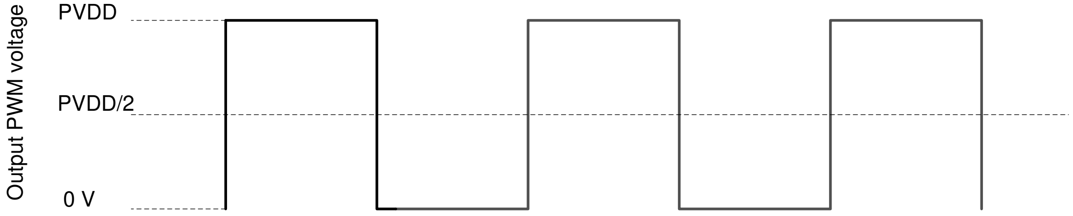


Figure 1-3. PWM Voltage Waveform

Figure 1-4 shows the inductor voltage and current waveforms drawn using these arguments.

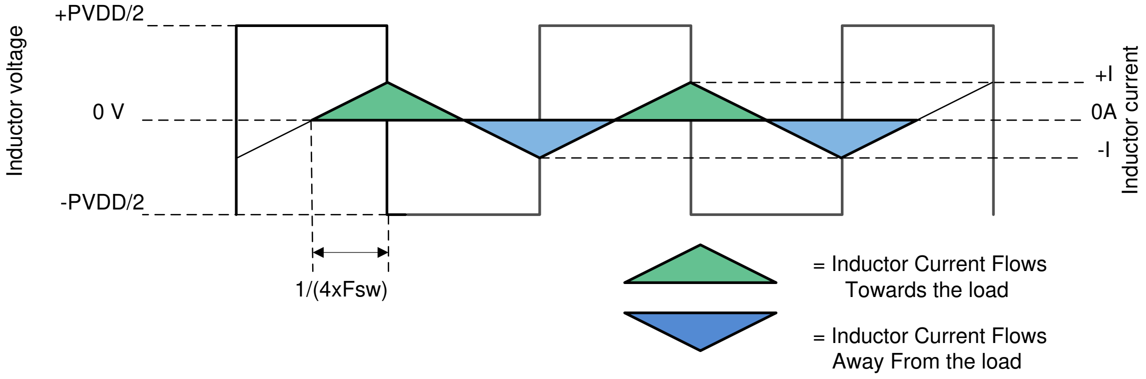


Figure 1-4. Inductor Voltage and Current

At idle, the positive and negative current flow through the inductor must be symmetrical and therefore centered around zero. Otherwise, there is a DC offset across the speaker and a constant average current flow through the load. The shaded regions in Figure 1-4 indicate the direction of current flow.

Using Figure 1-4, the peak ripple current at idle can be calculated.

$$I_{\mathrm{Ripple,\,Peak}} = \frac{\mathrm{PVDD}/2}{\mathrm{L}}\delta t$$

$$I_{\mathrm{Ripple,\,Peak}} = \frac{\mathrm{PVDD}}{2 \times \mathrm{L}} \times \frac{1}{4 \times f_{\mathrm{PWM}}}$$

$$I_{\mathrm{Ripple,\,Peak}} = \frac{\mathrm{PVDD}}{8 \times \mathrm{L} \times f_{\mathrm{PWM}}} \tag{1}$$

where

- L = inductor value
- f_{PWM} = PWM switching frequency

As the power voltage increases, the peak ripple current also increases. Consider increasing the inductance to reduce the output ripple current. On high-voltage applications, use a fourth-order filter configuration for better EMC performance. Figure 1-5 is a typical TAS6x84 LC filter configuration that can cover all voltage applications.

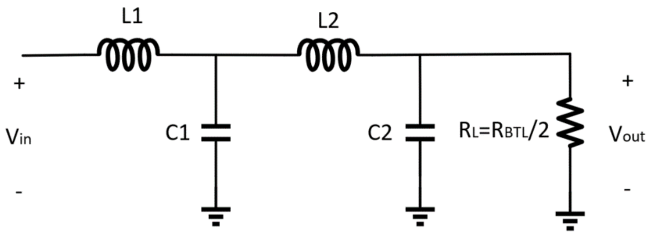


Figure 1-5. TAS6x84-Q1 Typical LC Filter Circuit (Half is Shown)

2 LC Filter Configuration

The LC filter value is selected for a critically damped, flat pass-band, and phase response. Two considerations when selecting components for LC filter is the cutoff frequency and Q factor or damping ratio. The cutoff frequency of LC filter and inductor value are based on the amplifier switching frequency, the ripple current is reduced such that only a small residual ripple voltage is present after the LC filter. TAS6x84-Q1 supports 384kHz, 480kHz, up to 2MHz high switching frequencies. Find the typical inductor and capacitor values using the calculations in the *LC Filter Design* application note. The 384kHz or 480kHz switching frequency typically uses a 10μH inductor, while the 2MHz switching frequency design can take advantage of a much smaller and lighter weight inductor in the range of 3.3μH. However, the LC filter configuration is also adjusted according to the power supply voltage, and the end system EMC specifications. Use a fourth-order filter configuration and higher inductance for high-voltage supply applications and special EMC conditions. Table 2-1 provides a quick LC filter selection guide.

Table 2-1. LC Filter Configuration

EMC Condition	Switching Frequency	LC Filter Configuration				Cutoff Frequency, 4Ω Load
		L1	C1	L2	C2	
Class-H enabled, or ≤ 24V power supply applications	384kHz, 480kHz	10μH	2.2μF	none	none	41.82kHz
High limitation on fundamental frequency		15μμH	2.2μF	none	none	29.79kHz
Standard configuration		10μH	1μF	1μH	0.22μF	43.85kHz
High limitation on full band		10μH	1μF	3.3μH	1μF	38.93kHz
Only for ≤ 24V power supply applications	2MHz	5.6μH	1μF	0.68μH	0.22μF	76.34kHz
Only for 14.4V battery power supply applications		3.3μH	1μF	0.68μH	0.22μF	113.19kHz

The frequency response of the LC filter is critical when selecting the component values for the inductor and capacitor. Figure 2-1 is the frequency response of the LC filter configurations with 4Ω load, assuming the inductor is linear and the DC resistance (DCR) is zero. The cutoff frequency of different LC filter is given in Table 2-1. The inductance and capacitor value chosen for 384kHz or 480kHz switching frequency are optimized on 4Ω load, slightly overdamped with 10μH / 1μF + 1μH / 0.22μF LC filter and slightly underdamped with 10μH + 2.2μF LC filter. While the response is a bit high underdamped with 3.3μH / 1μF + 0.68μH / 0.22μF LC filter for 2MHz switching frequency.

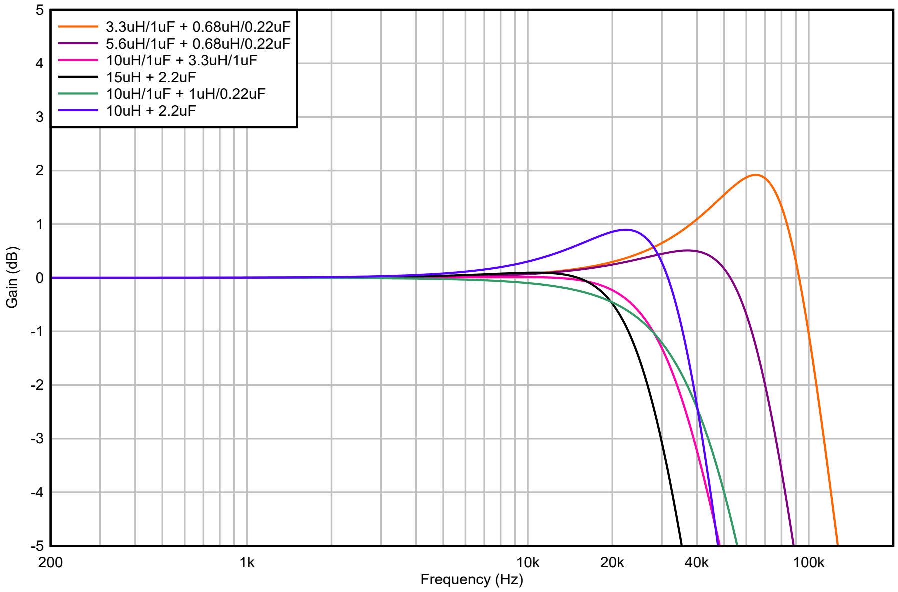


Figure 2-1. Frequency Response of LC Filter - 4Ω Load

The LC filter response also varies with speaker load impedance. The load impedance determines the damping ratio of the output LC filter and is classified as overdamped, critically damped, or underdamped. The equations for the single-ended LC filter shown in Figure 1-1 follow:

$$f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi\sqrt{L \times C}} \text{ Cutoff frequency of single-ended LC filter} \tag{2}$$

$$\omega_0 = 2\pi f_0 \text{ Conversion between radians and frequency in hertz} \tag{3}$$

$$Q = R_L\sqrt{\frac{C}{L}} \text{ Quality Factor Q} \tag{4}$$

$$\zeta = \frac{1}{2Q} = \frac{1}{2 \times R_L\sqrt{\frac{C}{L}}} \text{ Damping Ratio} \tag{5}$$

According to those calculations, load impedance determines the damping ratio of the output LC filter. Figure 2-2 is selected LC filter 10μH / 1μF + 1μH / 0.22μF frequency response with various speaker loads. The frequency response is seriously overdamped with 2Ω load, and seriously underdamped with 8Ω load. At high frequency, the peaks are generally harsh to the human ear and can also trigger the protection circuitry, such as overcurrent, of some amplifiers. However, overdamped filters result in attenuation of high-frequency audio content in the audio band.

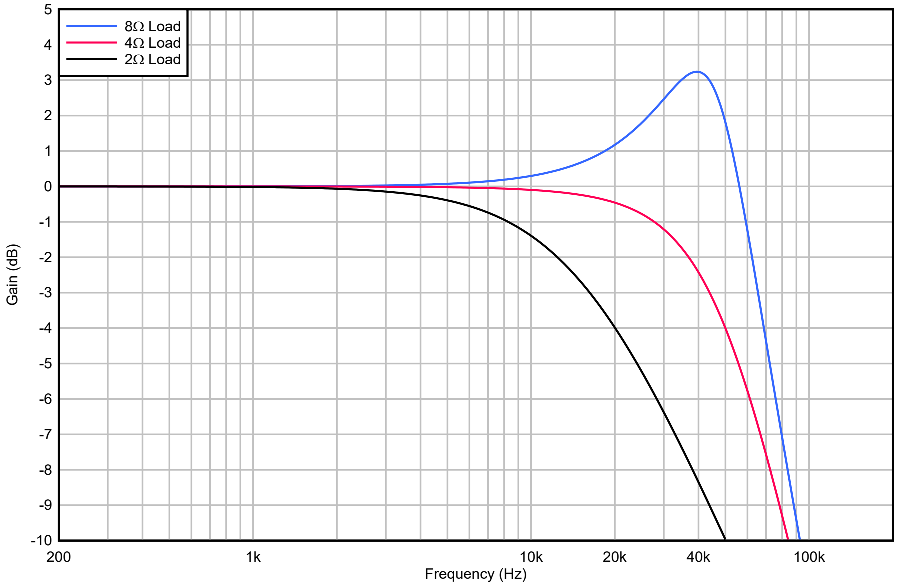


Figure 2-2. LC Filter Response With 10μH / 1μF + 1μH / 0.22μF

To help compensate for this effect and achieve a flat response, the TAS6x84-Q1 offers integrated and channel-based gain compensation biquads which are configurable by channel and are disabled by default. To enable the desired tuning, the respective coefficients need to be written to the DSP memory. Figure 2-3 and Figure 2-4 show the frequency response differences when enable and without tuning gain compensation biquads with the same load. A flat response is achieved after enabling the integrated compensation with a desirable equalizer setting. The guide of tuning gain compensation biquads is in Appendix A.

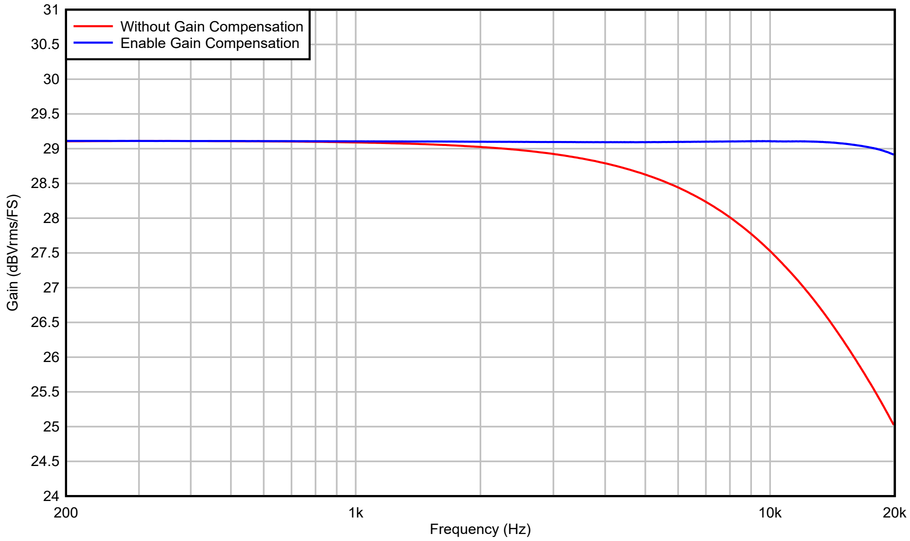


Figure 2-3. LC Filter Response With 10µH / 1µF + 1µH / 0.22µF - 2Ω, 24V PVDD

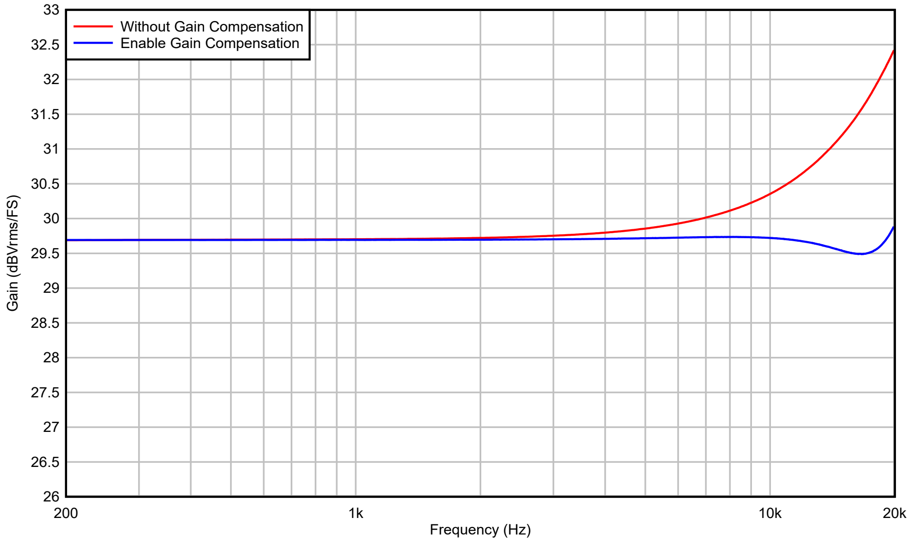


Figure 2-4. LC Filter Response With 10µH + 0.22µF - 8Ω, 45V PVDD

Figure 2-5 and Figure 2-6 show the TAS6584-Q1 2MHz switching frequency power efficiency at several power supplies. The power efficiency at a high supply voltage results in difficult thermal requirements, so the 2MHz switching frequency is not recommended on high supply voltage applications. At the 2MHz switching frequency, a 3.3µH inductor is only recommended on 14.4V power supply applications. Because of the increase in the power supply, increase the inductance to 5.6µH to reduce ripple current. A fourth-order filter configuration is also recommended at 2MHz switching frequency to meet end-system EMC specifications. While the power supply is higher than 24V, a 384kHz or 480kHz switching frequency is the best design. This document focuses on the LC filter performance on 480kHz switching frequency applications, because ripple current is lower than 384kHz switching frequency with same inductance.

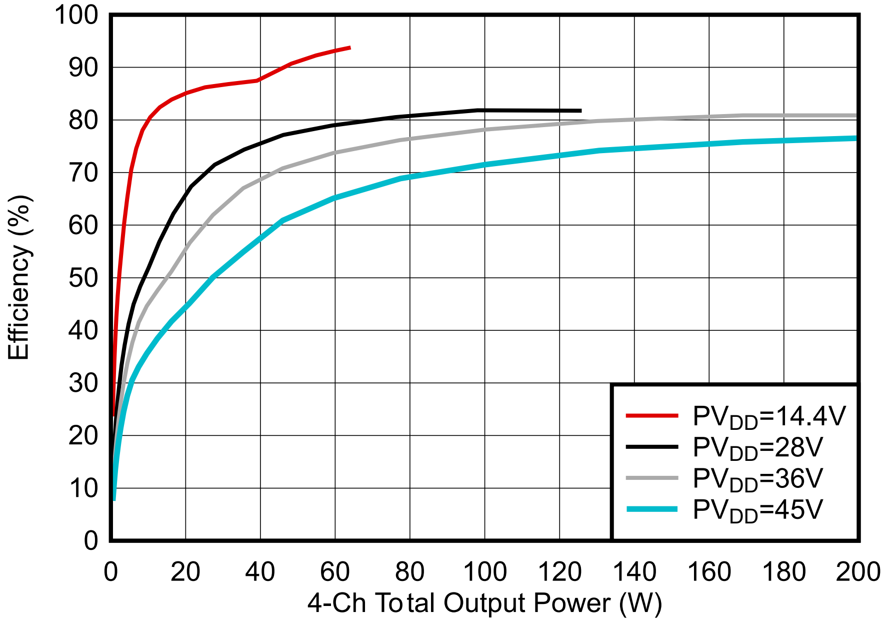


Figure 2-5. Efficiency vs Output Power - 8Ω, PVDD

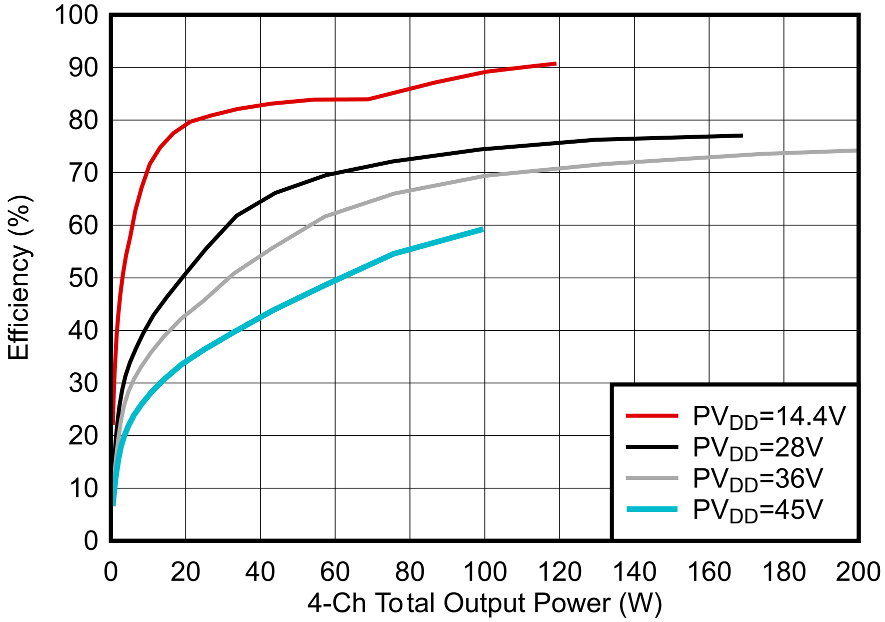


Figure 2-6. Efficiency vs Output Power - 4Ω, PVDD

3 Audio Performance

The LC filter configuration and components selection can significantly impact the audio performance THD+N, frequency response, and so forth. This section provides data found from data sheets and measured audio performance to illustrate the performance of various LC filter components.

3.1 Inductor Performance Guide

Inductance value, DCR, linearity and core loss are critical for the audio performance. Each factor detail influence is in the *LC Filter Design* and *Inductor Selection Guide for 2.1MHz Class-D Amplifiers* application notes. The selection inductor guide was created by referencing data sheets and measuring the THD+N for the inductors to illustrate inductor performance. The ranking is determined by the goal of the design. The goals are separated for output power into a load, THD, and physical dimensions.

The following tests were performed with the TAS6584-Q1 device typical applications: set up in 4 × BTL outputs with 2Ω, 4Ω, and 8Ω loads. The PWM switching frequency was set to 480kHz with PVDD supply of 24V, 35V, and 45V. Table 3-1 lists the inductors that were tested. Charts are created to compare the inductors that were tested based on the overall current handling current and all configurable LC filter configurations with different impedance loads.

Table 3-1. Inductor Specifications

Part Number	Inductance (µH)	Dimensions L × W × H (mm)	L_{SAT} (A)	L_{TEMP} (A)	DCR (mΩ)
Chilisin AMDCDY1010J0100MA2	10	10 × 9.5 × 10.85	12	5.8	22
Chilisin AMDCDY1010J0150MA2	15	10 × 9.5 × 10.85	10	3.6	40
Cyntec VAMV1009AA-100MM2	10	10.2 × 9.2 × 10.85	12	5.8	18
Cyntec VAMV1009AA-150MM2	15	10.2 × 9.2 × 10.85	9	4.5	34
Cyntec VAMV08089A-100MM2	10	8.15 × 8.0 × 8.9	8	4	33
Coilmaster CMI-CMMPP8055H1-100M	10	8.6 × 8.1 × 5	10.5	7	45
Coilmaster CMI-TMMPB11120HL-150M	15	11 × 11 × 12.5	11	8.5	40
Coilmaster CMI-TMMPB09120HL-150M	15	9 × 11 × 12.5	10.5	8	45
Sagami DBE1316HH-100M	10	15 × 10 × 16	11.1	6.2	9
Sagami DLM1623M-100M	10	15 × 15.9 × 23	15	6.4	9
Sagami DLM1623M-150M	15	15 × 15.9 × 23	11	5.2	17.6
Sagami 7W14A-150M	15	15.5 × 14 × 16	8.4	5.2	14
Sunlord AMPR1009H-100MT	10	10.2 × 9.2 × 10.8	12	9	18
Murata DFE322520FD-1R0M=P2	1	3.2 × 2.5 × 2	7.5	4.1	22

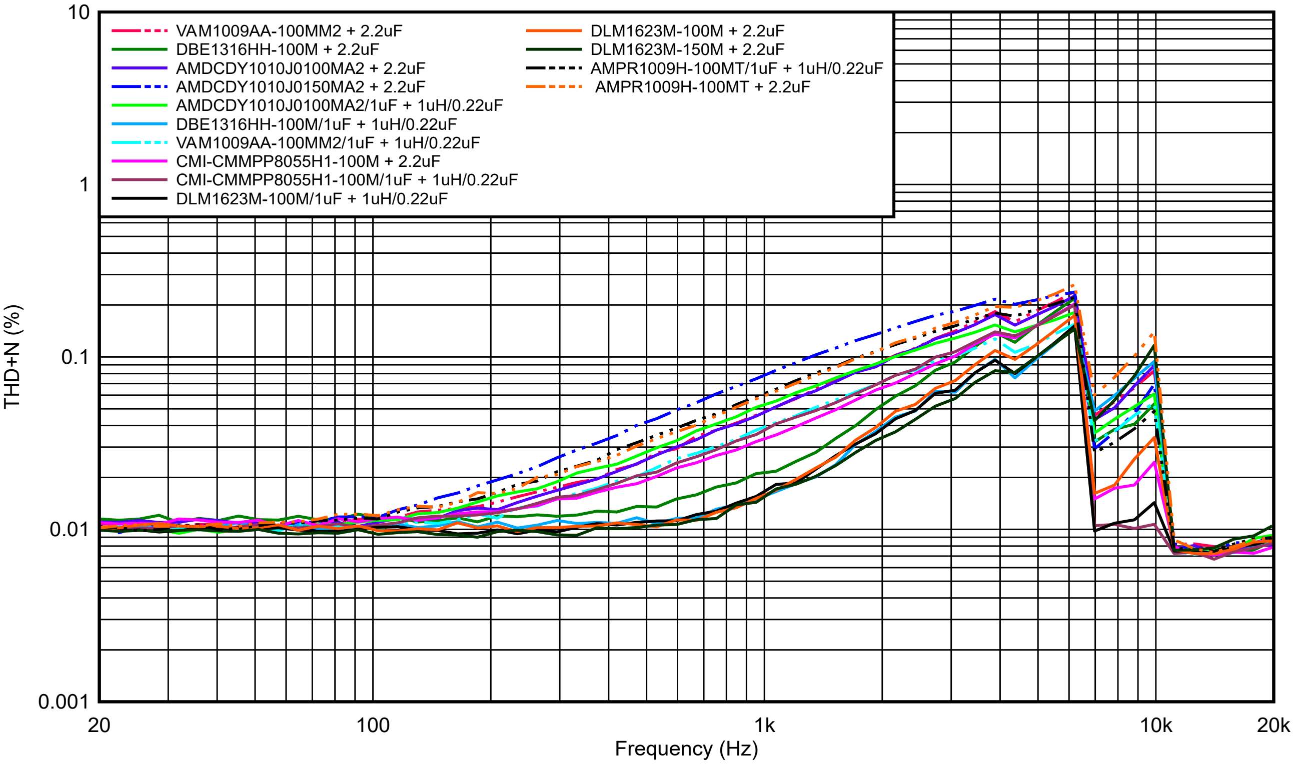


Figure 3-1. THD vs Frequency - 2Ω, 24V PVDD

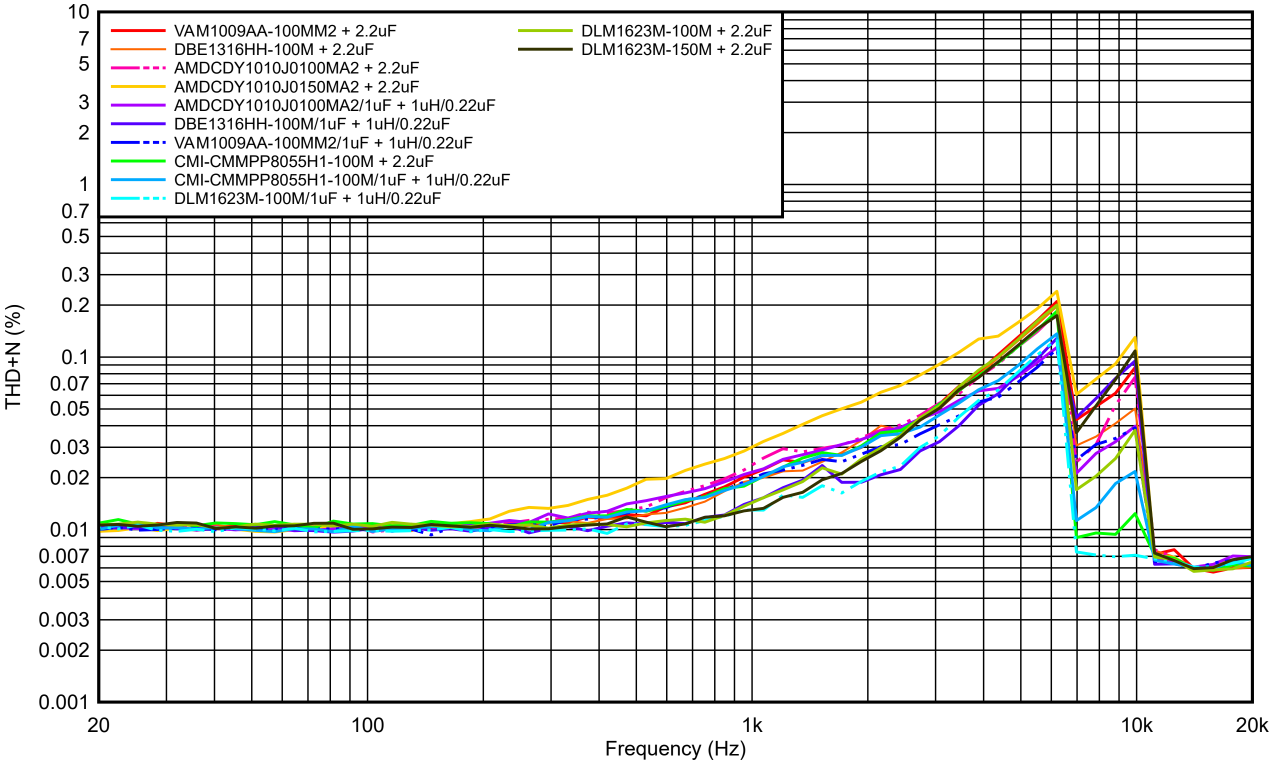


Figure 3-2. THD vs Frequency - 4Ω, 35V PVDD

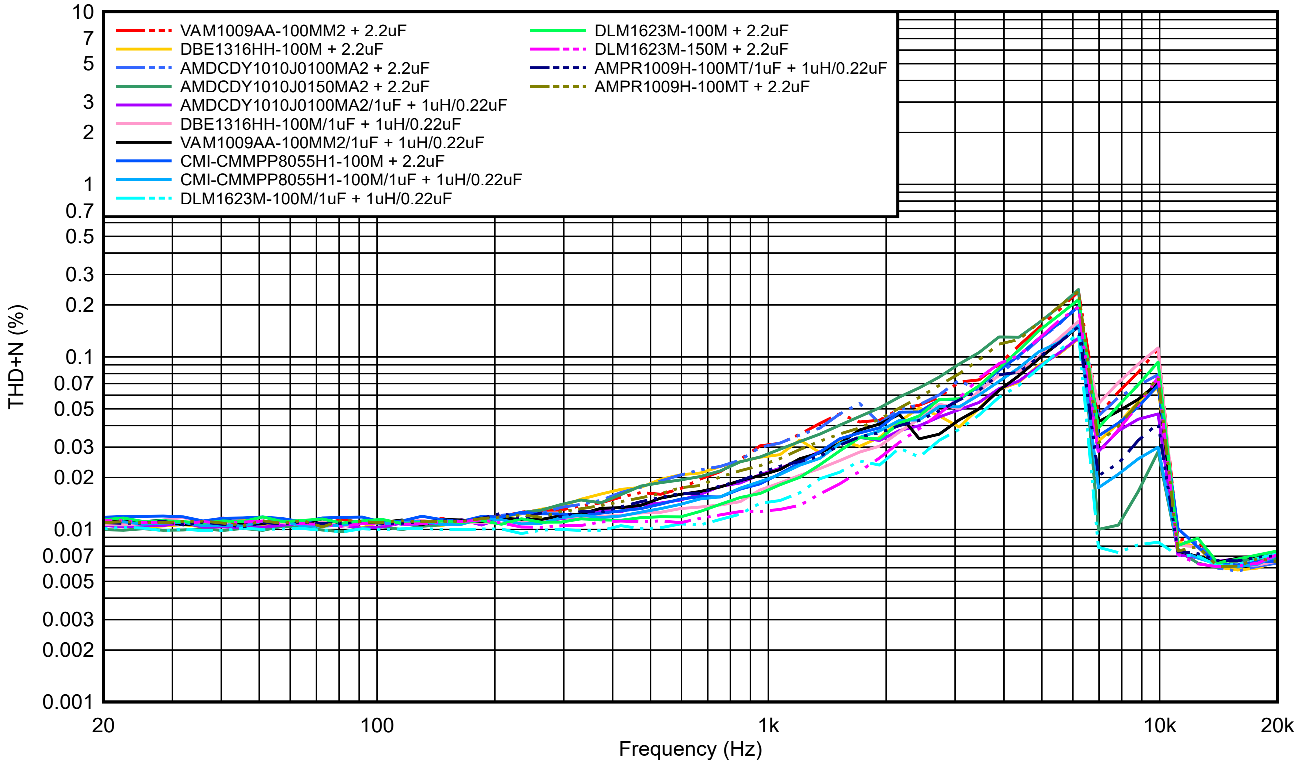


Figure 3-3. THD vs Frequency - 4Ω, 45V PVDD

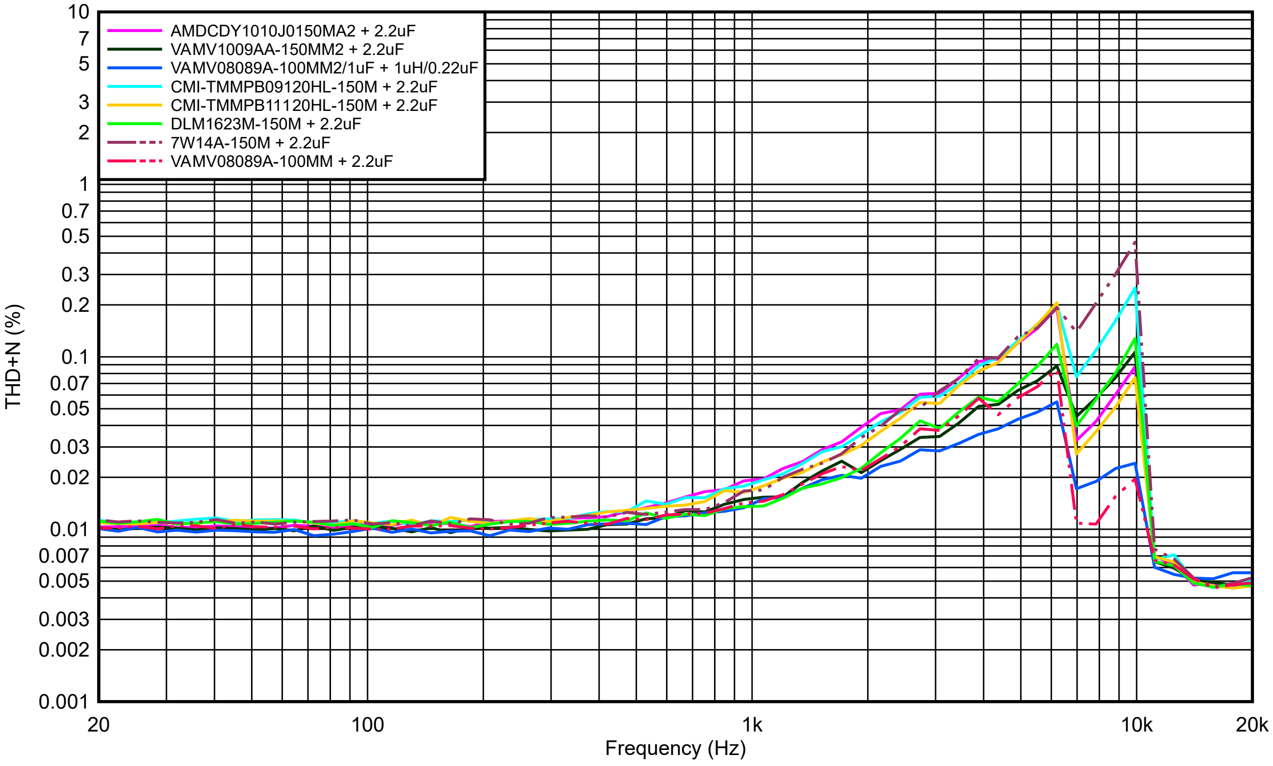


Figure 3-4. THD vs Frequency - 8Ω, 35V PVDD

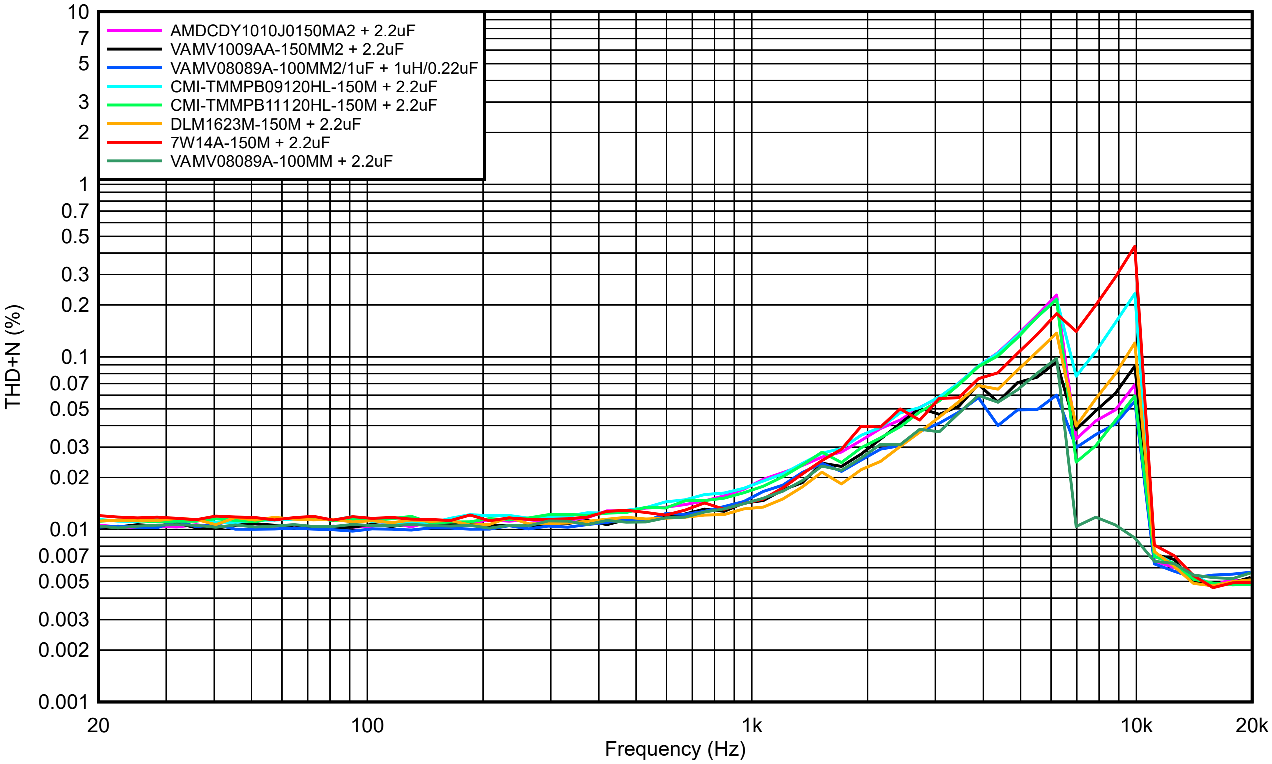


Figure 3-5. THD vs Frequency - 8Ω, 45V PVDD

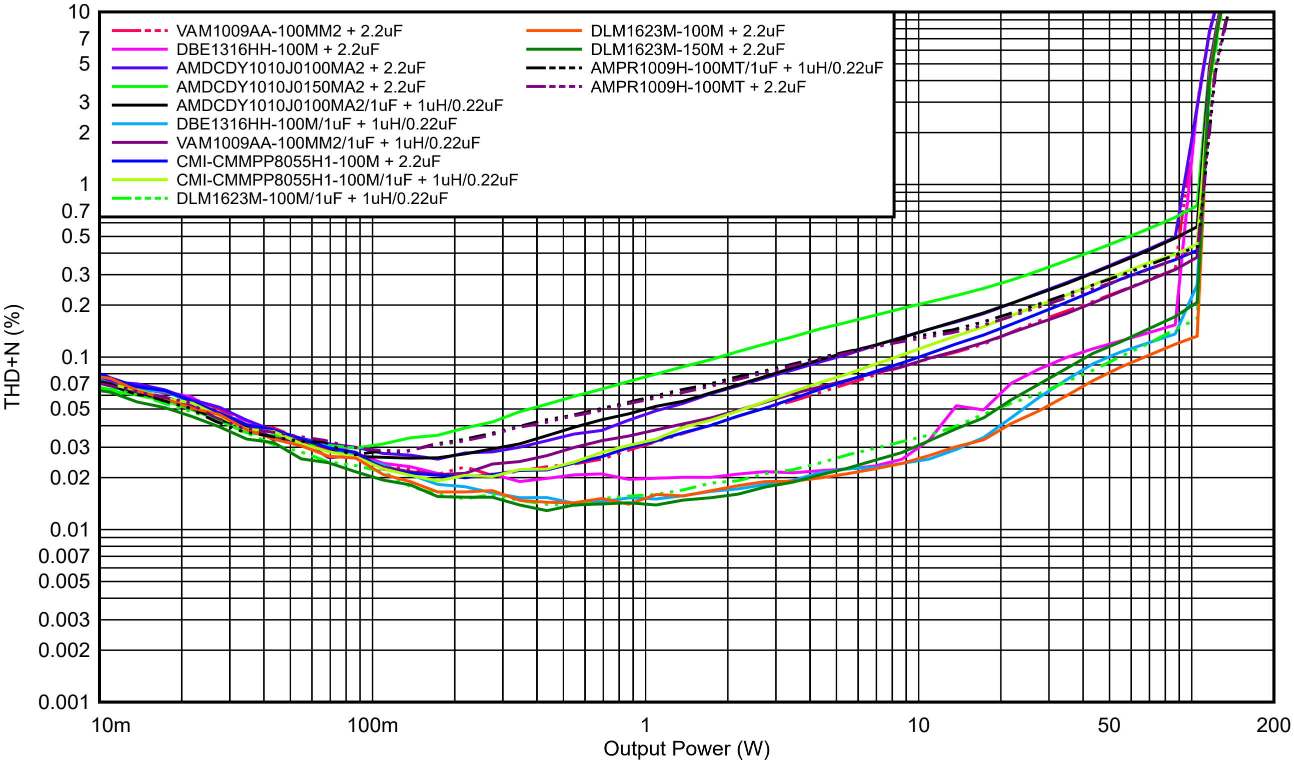


Figure 3-6. THD vs Power - 2Ω, 24V PVDD

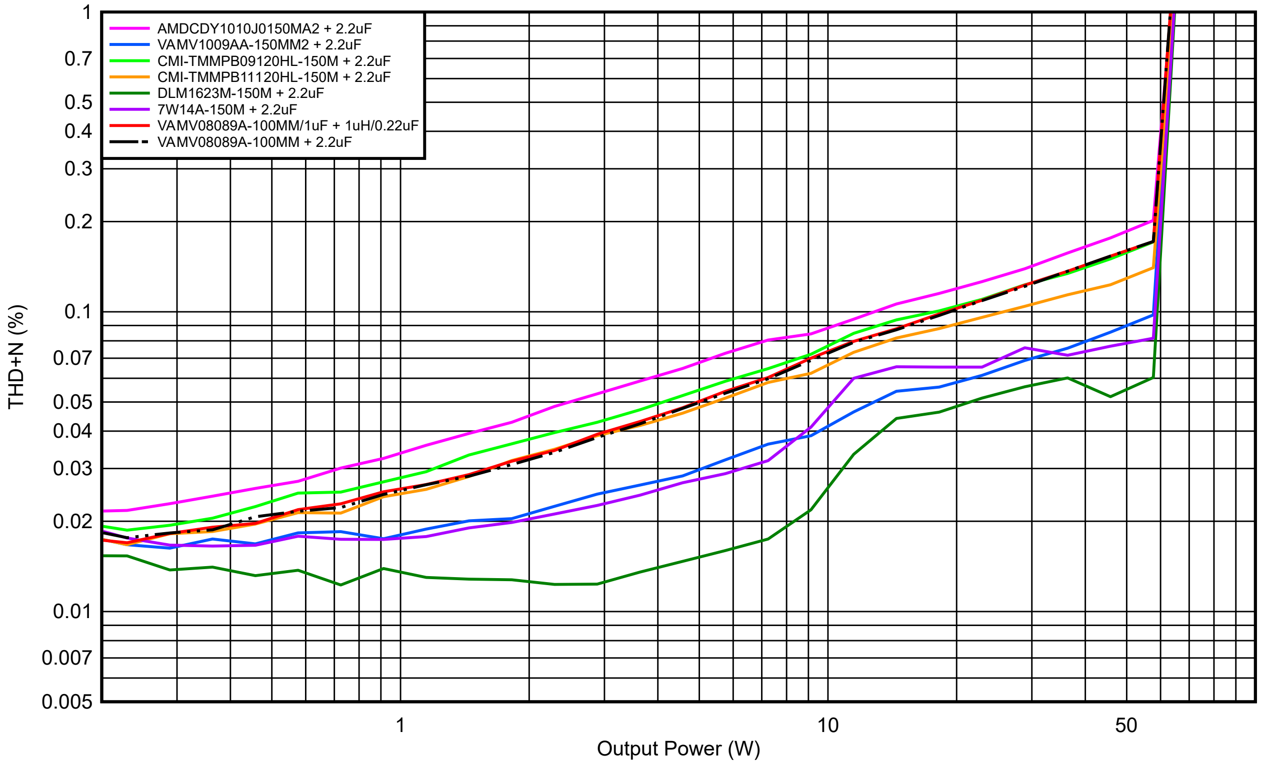


Figure 3-7. THD vs Power - 4Ω, 24V PVDD

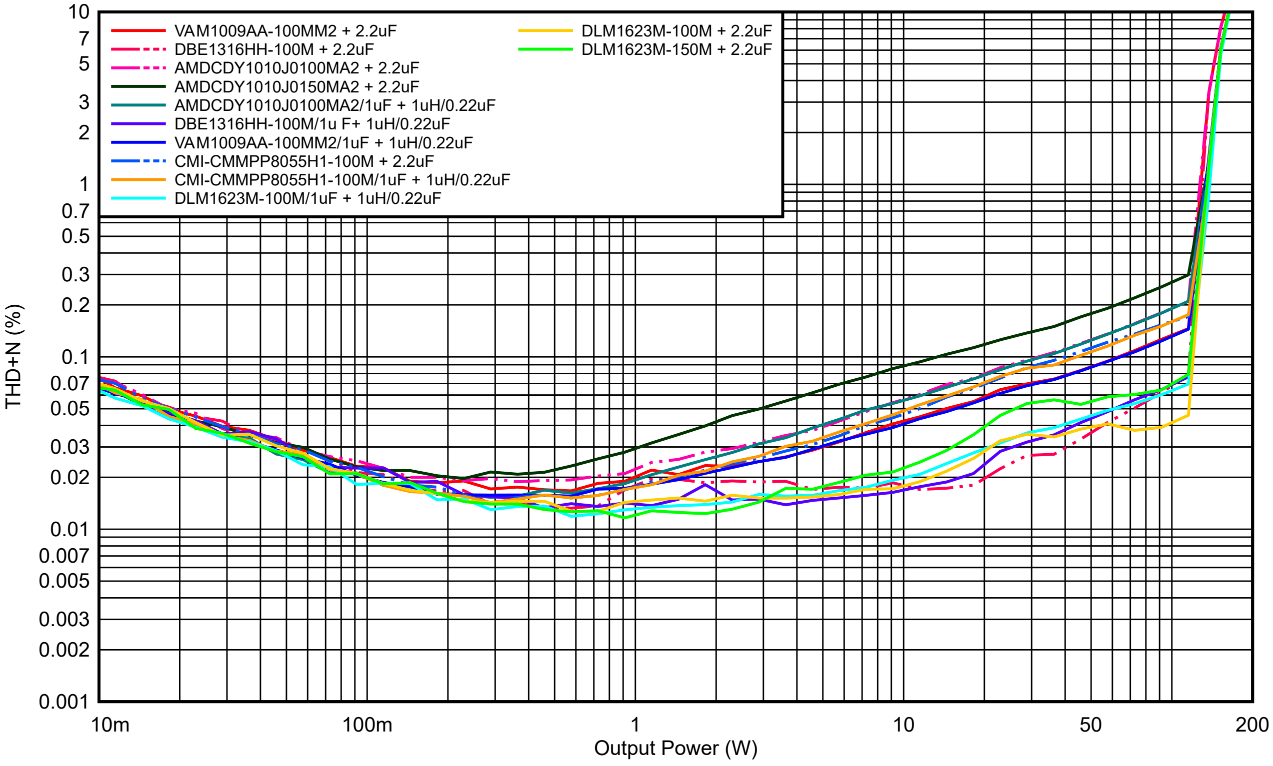


Figure 3-8. THD vs Power - 4Ω, 35V PVDD

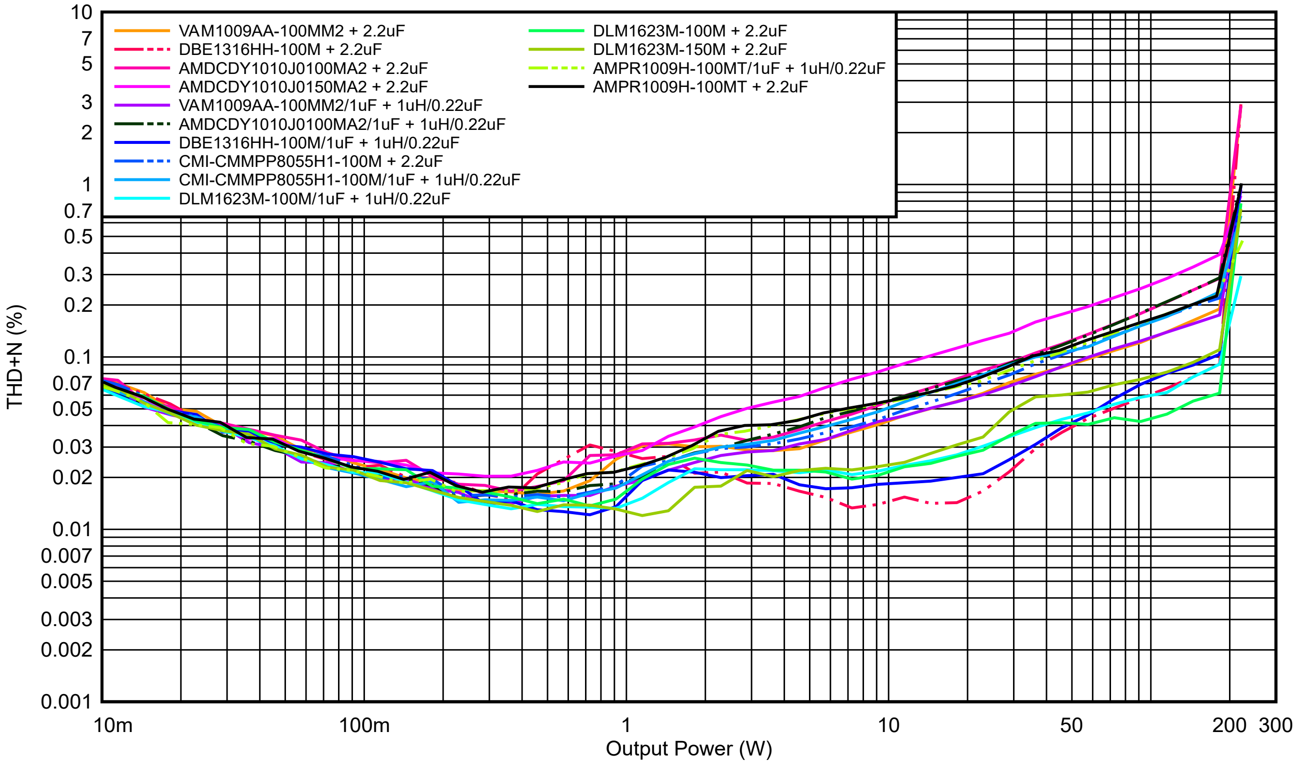


Figure 3-9. THD vs Power - 4Ω, 45V PVDD

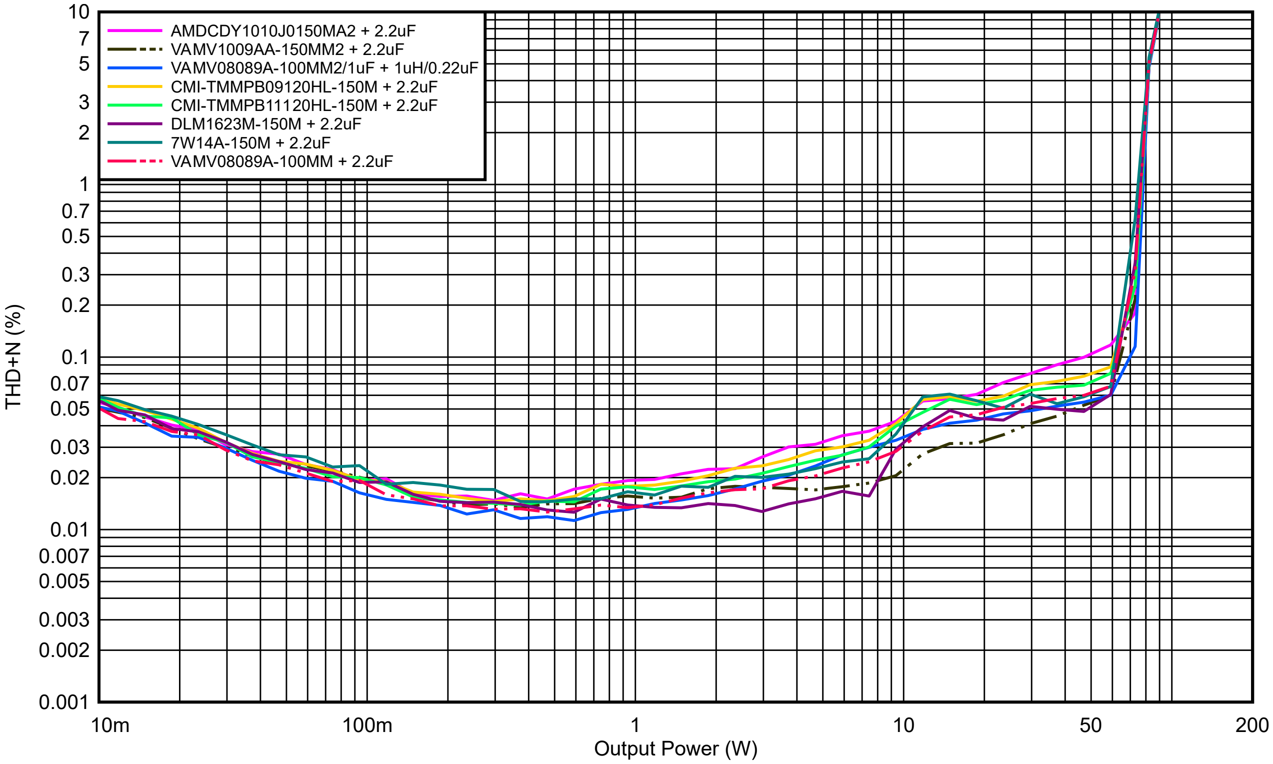


Figure 3-10. THD vs Power - 8Ω, 35V PVDD

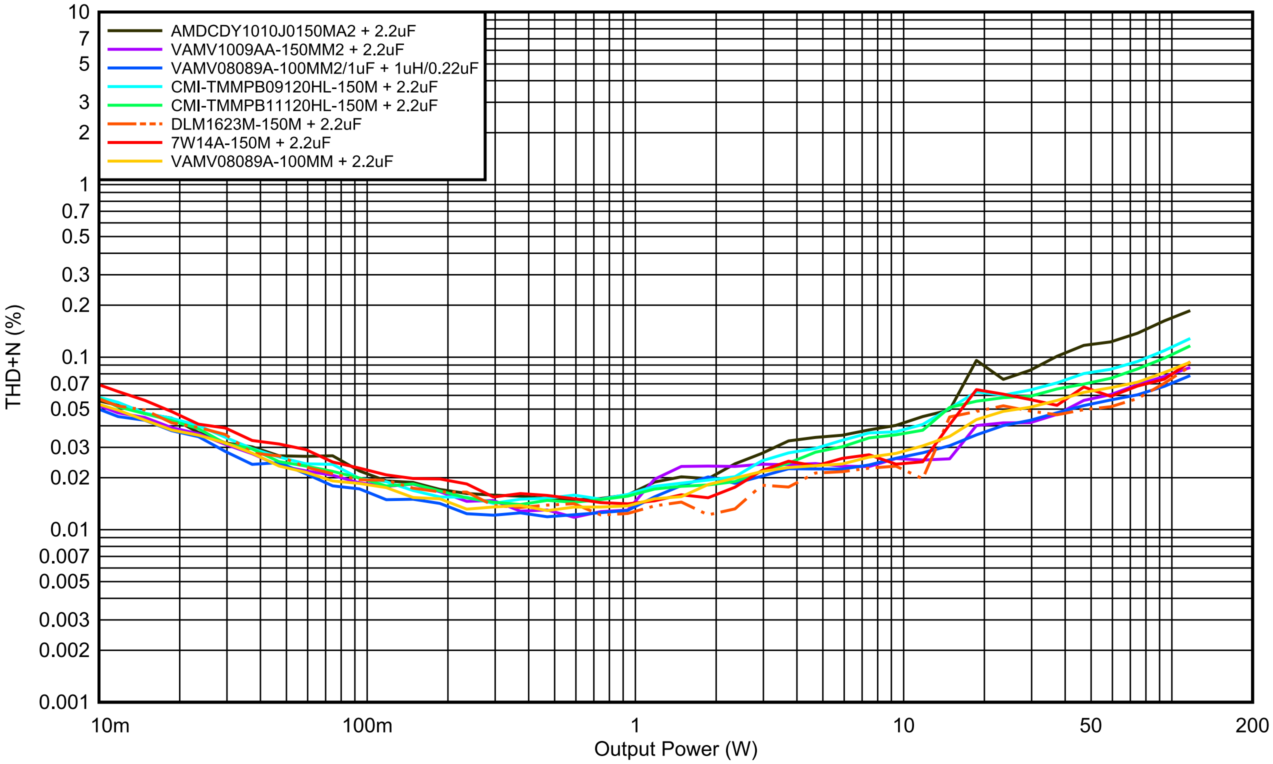


Figure 3-11. THD vs Power - 8Ω, 45V PVDD

3.2 Capacitor Selection

For the best audio performance, component selection is critical to maintain a flat LC filter frequency response and minimize distortion. The *capacitor considerations* section of the *LC Filter Design* application note has a detailed discussion of the key parameters and trade-offs for choosing a capacitor for high-power class-D audio-amplifier applications.

Multilayer ceramic chip capacitors (MLCC) are some of the most standardized components used in electronics today because of small size and low cost. This guide test data selected ceramic capacitors for automotive with optimized key parameters to minimize impact on audio and EMC performance. The capacitors selected have enough rated voltage on 45V, low ESR, and a desirable size to minimize DC bias voltage impact. Table 3-2 lists the capacitors that were used on the LC filter and tested on audio performance. Detailed ratings and specifications can be obtained through capacitor manufacturers for using capacitors safely in a system.

Table 3-2. Capacitor Specifications

Part Number	Capacitance	Size Code	Rated Voltage	Temperature Characteristics
GCJ31CC72A225KE01	2.2µF	1206 (3216M)	100V	X7S (EIA)
GCJ31CR72A105KA01L	1µF	1206 (3216M)	100V	X7S (EIA)
GCM21BR71H105KA03L	0.22µF	0805 (2012M)	50V	X7R (EIA)

4 Summary

LC filter design is critical for automotive class-D audio amplifier. Select the LC filter configuration according to the switching frequency, power system, thermal, audio performance, and the end-system EMC specifications. From the results of the LC filter configuration with different inductors study, it is clear that the inductor plays a large role in the audio performance. The inductance value, DCR, and linearity factor into the total system performance and must be considered based on the design goals of a specific application.

For the TAS6x84-Q1 family of devices, the fourth-order filter configuration 10μH / 1μF + 1μH / 0.22μF is standard configuration for better audio performance due to the reduced ripple current with higher inductance. From the TAS6584-Q1 device test data, the audio performance of 10μH / 1μF + 1μH / 0.22μF LC filter is better than 10μH + 2.2μF configuration with same 10μH part number inductor.

DCR also must be considered on high-output power applications. Although a 10μH / 1μF + 1μH / 0.22μF configuration can show improved power dissipation for low output power due to reduced ripple current, if the application has high DCR, the losses can be greater at high currents than a 10μH + 2.2μF configuration with higher ripple current. From the test data of TAS6584-Q1 device, the output power capacity with the inductor which has lower DCR is higher than the inductor which has higher DCR at same LC filter configuration. And the inductor which has lower DCR also has better THD + N performance on high output power.

With different impedance loads, some LC filter configurations can make frequency response seriously overdamped or seriously underdamped at high frequency. Besides LC filter adjustment, tuning TAS6x84-Q1 family internal gain compensation biquads helps achieve a flat frequency response. Appendix A introduces the detailed tuning guide.

Detail ratings and specifications of inductance value, handling current and linearity can be obtained through inductor manufacturers. Actual inductance value with current increase greatly affects audio performance. Higher inductance value gets better audio performance. Evaluate the size and price of the inductors before making the final selection. Although the price of the inductors has not been part of this study, typically, the smaller the inductor, the lower the cost.

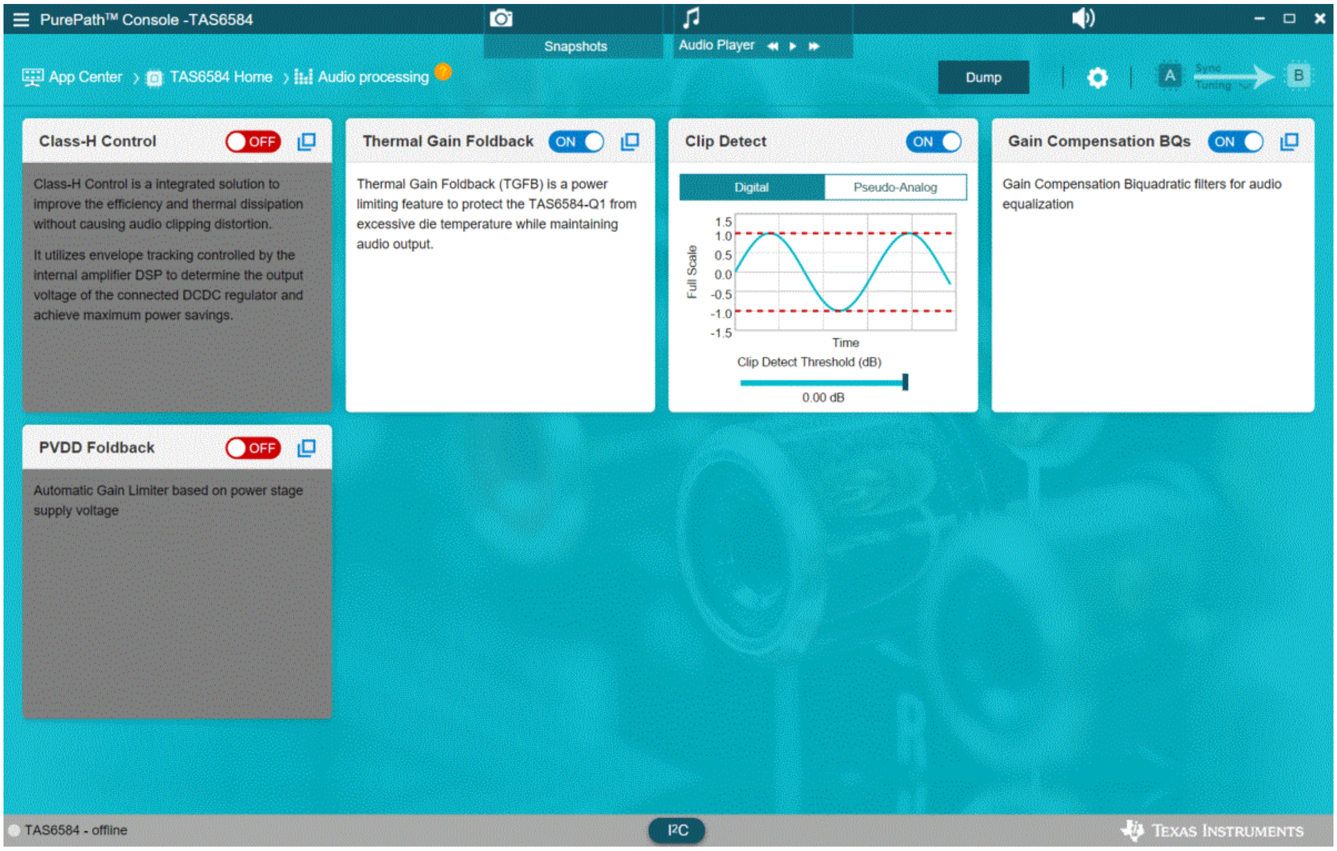
5 References

- Texas Instruments, *LC Filter Design Application Note*
- Texas Instruments, *Inductor Selection Guide for 2.1MHz Class-D Amplifiers Application Note*

A Gain Compensation Biquads

The TAS6584-Q1 PPC3 GUI software provides an easy way to enable gain compensation biquads (BQ) and adjust settings to optimize the flat LC filter frequency response.

Click on the *Audio Processing Options box* in the *Home* window, and toggle *Gain Compensation BQs* to *ON* (see Figure A-1).



Class-H Control is a integrated solution to improve the efficiency and thermal dissipation without causing audio clipping distortion.

It utilizes envelope tracking controlled by the internal amplifier DSP to determine the output voltage of the connected DCDC regulator and achieve maximum power savings.

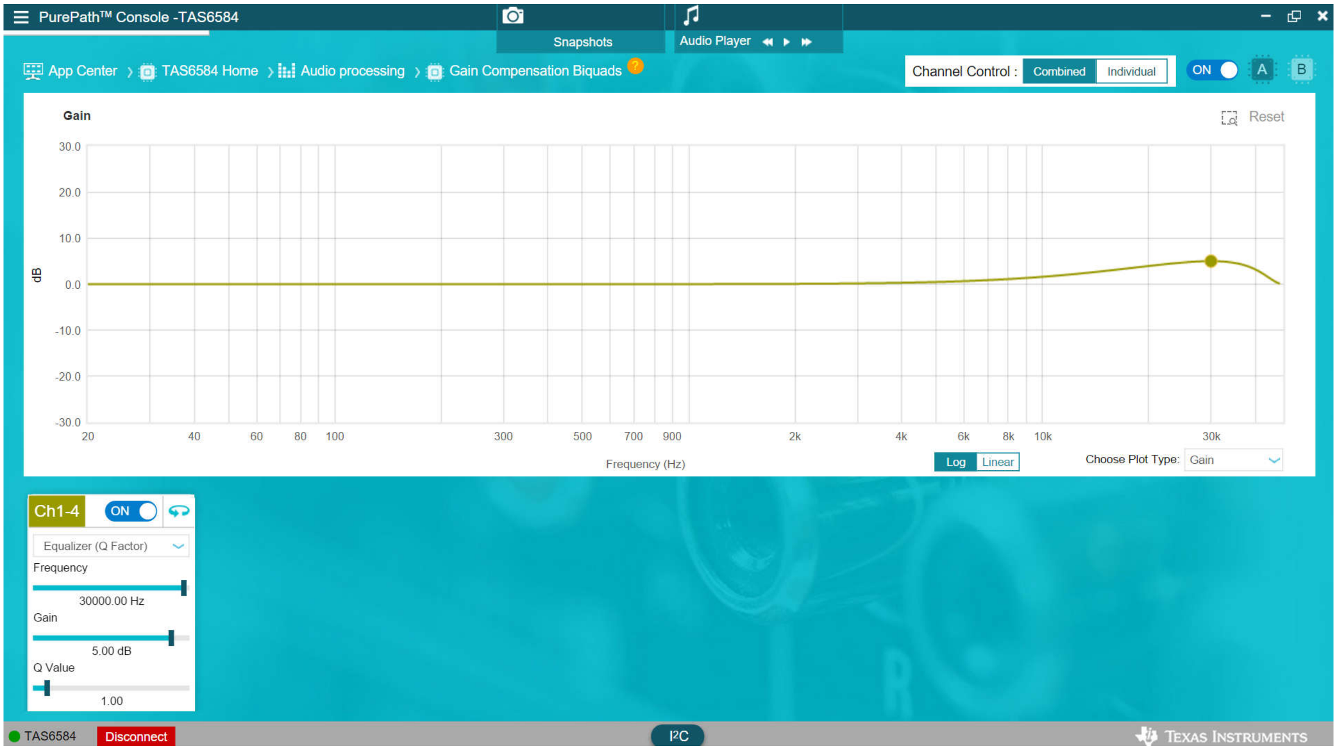
Thermal Gain Foldback (TGFB) is a power limiting feature to protect the TAS6584-Q1 from excessive die temperature while maintaining audio output.

Gain Compensation Biquadratic filters for audio equalization

Automatic Gain Limiter based on power stage supply voltage

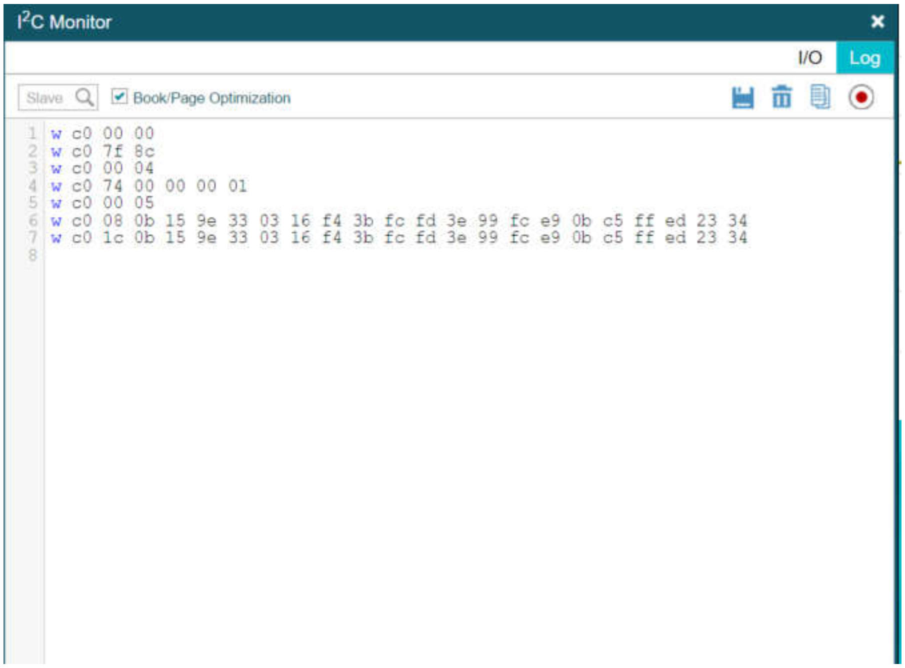
Figure A-1. TAS6584-Q1 GUI Audio Processing Window

On the *Gain Compensation Biquads* page, all channels are controlled by the same setting when the *Combined* option is selected. Each channel can also have a separate configuration through the *Individual* option. Click *ON* the on and off slider of channels to turn an Equalizer process on (Q Factor). The *I2C Monitor* window (click lower middle I2C button in Figure A-2) can be used to record the integrated DSP registers setting for the Equalizer. Figure A-2 and Figure A-3 are example of the tuning Equalizer setting of Figure 2-3 (2Ω load with LC filter VAM1009AA-100MM / 1µF + 1µH / 0.22µF). Figure A-4 and Figure A-5 are examples of the tuning Equalizer setting of Figure 2-4 (8Ω load with LC filter VAM1009AA-100MM + 2.2µF).



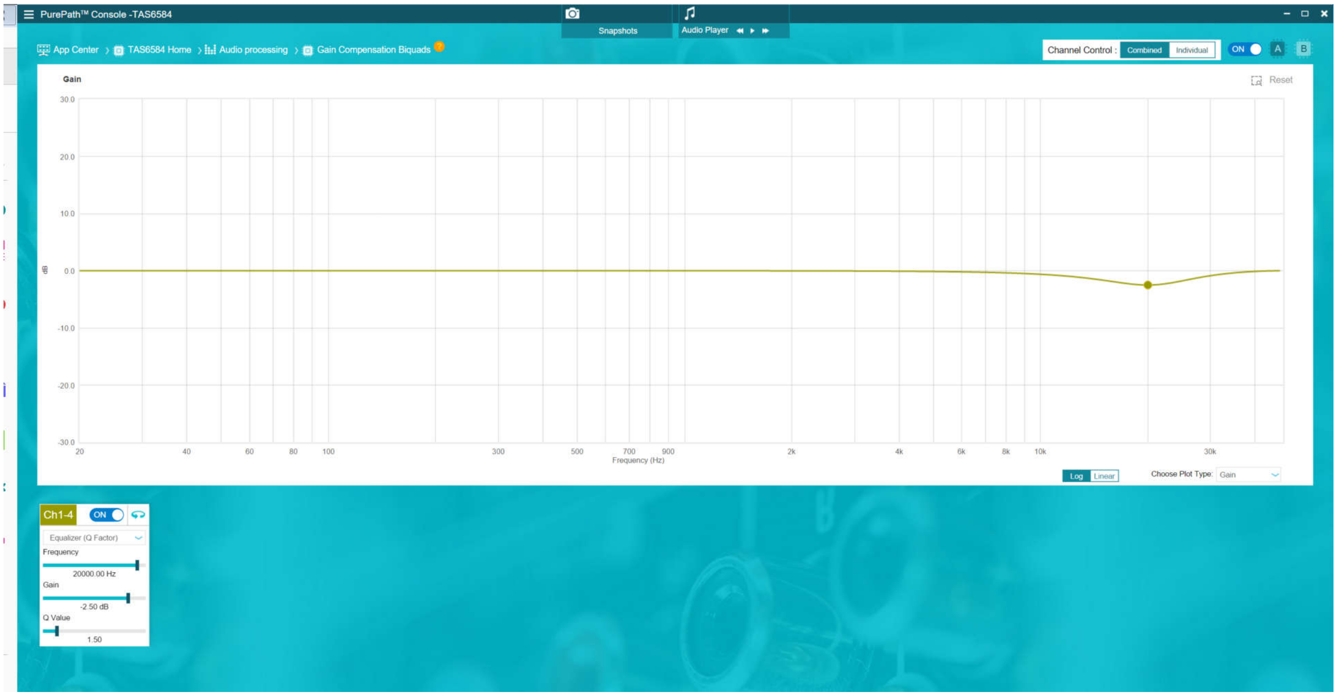
Frequency
30000.00 Hz
Gain
5.00 dB
Q Value
1.00

Figure A-2. TAS6584-Q1 GUI Gain Compensation Biquads Page - 2Ω



```
w c0 00 00
w c0 7f 8c
w c0 00 04
w c0 74 00 00 00 01
w c0 00 05
w c0 08 0b 15 9e 33 03 16 f4 3b fc fd 3e 99 fc e9 0b c5 ff ed 23 34
w c0 1c 0b 15 9e 33 03 16 f4 3b fc fd 3e 99 fc e9 0b c5 ff ed 23 34
```

Figure A-3. TAS6584-Q1 GUI I2C Monitor - 2Ω



Equalizer (Q Factor)

Frequency: 20000.00 Hz

Gain: -2.50 dB

Q Value: 1.50

Figure A-4. TAS6584-Q1 GUI Gain Compensation Biquads Page - 8Ω

☑ Book/Page Optimization

```
w c0 00 00
w c0 7f 8c
w c0 00 04
w c0 74 00 00 00 01
w c0 00 05
w c0 08 07 e3 d5 c5 f1 02 56 e2 07 3a f0 cb 0e fd a9 1e f8 e1 39 70
w c0 1c 07 e3 d5 c5 f1 02 56 e2 07 3a f0 cb 0e fd a9 1e f8 e1 39 70
```

Figure A-5. TAS6584-Q1 GUI I2C Monitor - 8Ω

Trademarks

All trademarks are the property of their respective owners.

IMPORTANT NOTICE AND DISCLAIMER

TI PROVIDES TECHNICAL AND RELIABILITY DATA (INCLUDING DATA SHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES “AS IS” AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS AND IMPLIED, INCLUDING WITHOUT LIMITATION ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE OR NON-INFRINGEMENT OF THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for skilled developers designing with TI products. You are solely responsible for (1) selecting the appropriate TI products for your application, (2) designing, validating and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, regulatory or other requirements.

These resources are subject to change without notice. TI grants you permission to use these resources only for development of an application that uses the TI products described in the resource. Other reproduction and display of these resources is prohibited. No license is granted to any other TI intellectual property right or to any third party intellectual property right. TI disclaims responsibility for, and you will fully indemnify TI and its representatives against, any claims, damages, costs, losses, and liabilities arising out of your use of these resources.

TI’s products are provided subject to TI’s Terms of Sale or other applicable terms available either on ti.com or provided in conjunction with such TI products. TI’s provision of these resources does not expand or otherwise alter TI’s applicable warranties or warranty disclaimers for TI products.

TI objects to and rejects any additional or different terms you may have proposed.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265

Copyright © 2024, Texas Instruments Incorporated